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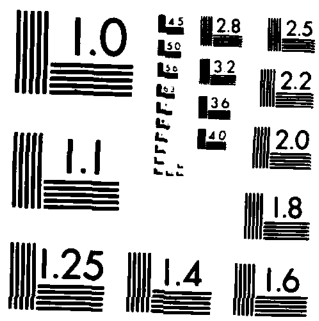

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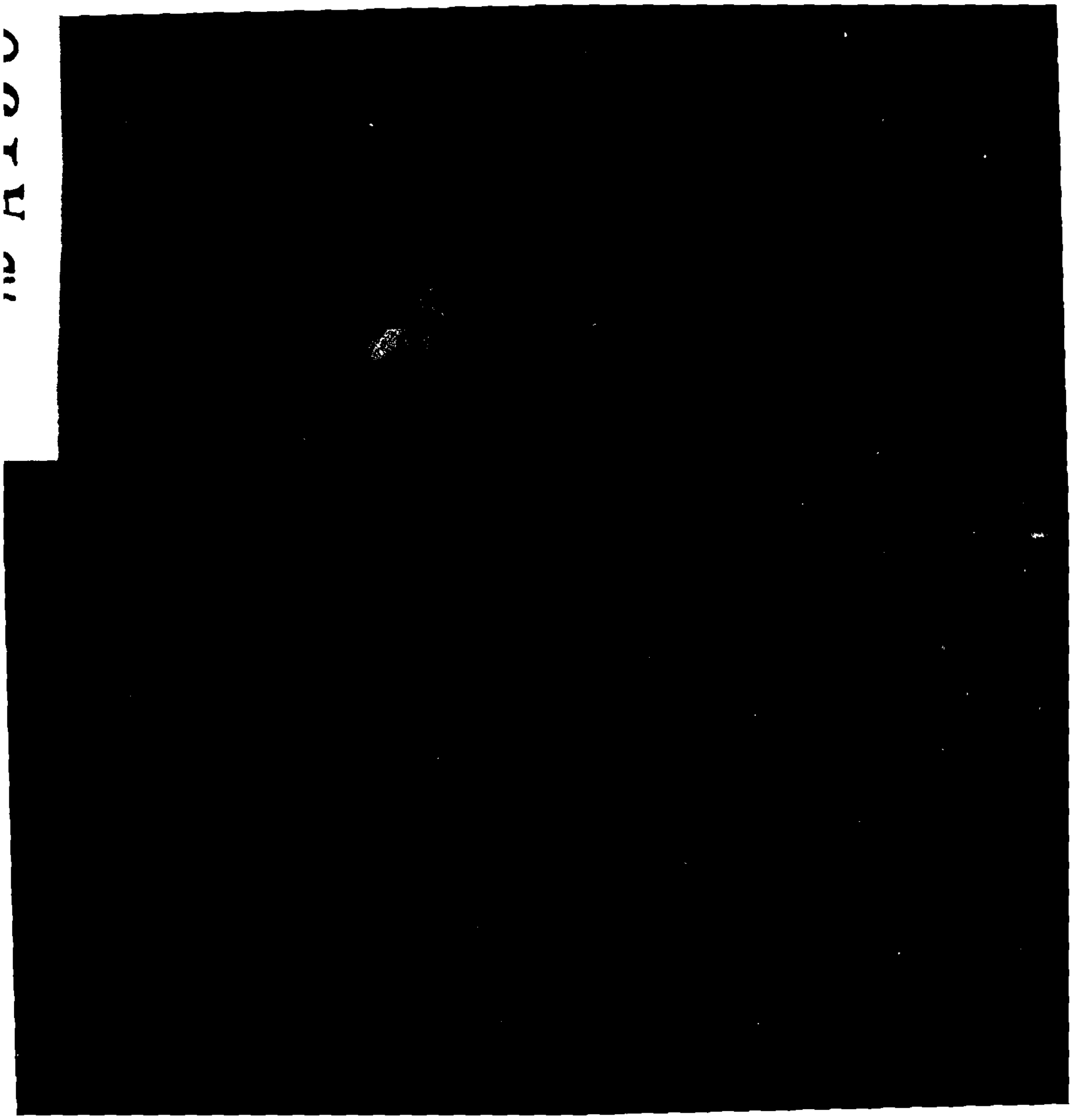

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A scheme is presented for the determination of the electron density and temperature in a background gas surrounding a laser produced plasma. The background gas (N_2) is photoionized by the ionizing radiation from the laser produced plasma. Band intensities of 3914Å and 3371Å from N_2^+ and N_2 are utilized for the determination of the state of the background plasma.

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THE ELECTRON DENSITY AND TEMPERATURE IN THE PHOTOIONIZED BACKGROUND GAS (N_2) SURROUNDING A LASER PRODUCED PLASMA

CONTENTS

THE ELECTRON DENSITY AND TEMPERATURE IN THE PHOTOIONIZED BACKGROUND GAS (N_2) SURROUNDING A LASER PRODUCED PLASMA

1. INTRODUCTION

The early time phenomena of a nuclear detonation can be simulated in the laboratory by focusing a high power laser onto a target. The laser produced plasma expands into a suitable background gas which is swept, compressed and ionized by the expanding plasma. Various interesting physical processes, such as coupling mechanisms can be studied in the laboratory.

The high density and high temperature plasma, however, emits radiation which photoionizes the background gas ahead the plasma expansion into the gas. Such a photoionized region resembles what is generally called the UV-Fireball in high altitude nuclear detonations. The state of the background gas and its degree of ionization can provide informantion on the amount of ionizing radiation absorbed in the gas as well as on debris-gas coupling.

In this report we describe a theoretical approach to determine the state of the photoionized background gas, i.e. the electron density and the electron temperature. This approach is based on spectroscopic quantities which can be measured, and is in support of the NRL experiments[1] on the early time phenomena.

For a background gas of nitrogen (N_2) the intensities of two bands emissions, one at 3914Å and the other at 3371Å can be utilized to determine the electron density and the electron temperature. These emissions, at 3914Å and 3371Å are the (0,0) transitions in the first negative and the second positive bands systems of N_2^+ and N_2, respectively.

This report gives the description for the calculations of these intensities by discussing the excitation and deexcitation mechanisms that affect the band intensities. It provides the appropriate cross sections,

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quenching coefficients and radiative decay rates which are essential for these calculations. Finally the report utilizes the formalism to calculate the electron density and the electron temperature in the NRL experiment for two background gas pressures of 5 Torr and 1.5 Torr.

2. NITROGEN EMISSION BANDS FOR PLASMA DIAGNOSTICS

The nitrogen molecule and its ion have numerous bands[2] which emit in the ultraviolet, visible and infrared. Many of these bands can be used for diagnostics of nitrogen plasmas. Two specific bands, however, the first negative and the second positive, shown[3] in Fig. 1, have often been utilized for plasma diagnostics and as a measure of electron and x-ray energy depositions[4-10] in N_2 and Air. The strongest transitions in these bands are the (0,0) transitions and are at 3914Å from the first negative band and 3371Å from the second positive band. The excitation mechanisms and various parameters of interest to these two bands have been reviewed by Ali[11] and are discussed here briefly.

2.1 THE 3914Å BAND

The 3914Å band corresponds to the (0,0) transition in the first negative bands system ($B^2\Sigma \rightarrow X^2\Sigma$) of N_2^+. The upper level of this transition has a weighted[12] life time of 62.5 nsec which implies a total decay rate of $1.6\times10^7 sec^{-1}$. Using the relevant Frank Condon factors[13] one obtains a rate of $1.04\times10^7 sec^{-1}$ for the (0,0) transition. In addition to the radiative decay, the upper level for the 3914Å transition is quenched by N_2 according to the following reaction

$$N_2^+(B,0) + N_2 \rightarrow N_2^+(X) + N_2 \tag{1}$$

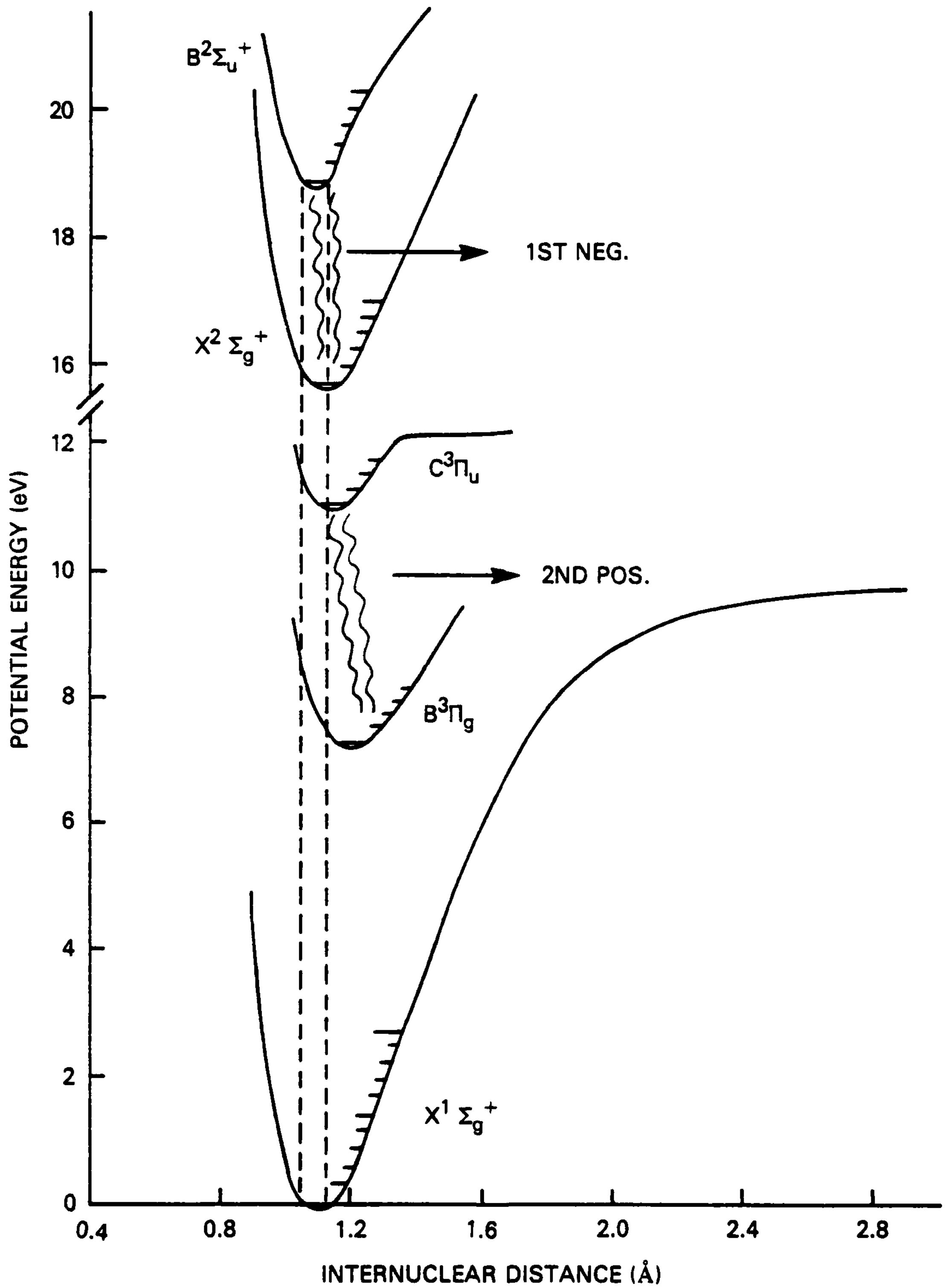

Fig. 1 The partial energy diagram of N_2 and N_2^+ where emissions from the first negative and the second positive bands are indicated.

A weighted average[11] for the quenching rate coefficient for process (1), based on various measurements, is $4.6 \times 10^{-10} cm^3/sec$.

The upper level of the first negative band, $N_2^+(B)$, is produced by photoionization as are the other ionization continua of N_2^+. However, this ionization contiuum represents[14] < 10% of the total ionization of N_2 for radiation of $\lambda < 650Å$. The dominant excitation of the 3914Å, on the other hand, results from electron collision with the ground state of the ion, according to

$$e + N_2^+ (X) \rightarrow N_2^+ (B,0) + e \tag{2}$$

The cross section for this process has been measured by Lee & Carlton[15] and by Crandall, et al[16] and are shown in Figure 2. However, the measurement of Lee and Carlton[15] is too high as a rate coefficient determination[17] have indicated previously. The reverse process of reaction (2) can contribute to the deexcitation when the electron density is high.

2.2 THE 3371Å BAND

The 3371Å band represents the (0,0) in the second positive bands system of N_2 which correspond to the $C^3\pi\ (\bar{v}) \rightarrow B^3\pi\ (\bar{\bar{v}})$ transitions. The lifetime of the upper level, $C^3\pi\ (v = o)$ has been measured and calculated (see Ref. 11 for details). A weighted average of the measurements yield 36.6 nsec for v = o state, which implies a radiative decay rate of $2.7 \times 10^7 sec^{-1}$. Using the appropriate Frank Condon factors[18] one obtains a rate of $1.22 \times 10^7 sec^{-1}$ for the 3371Å transition.

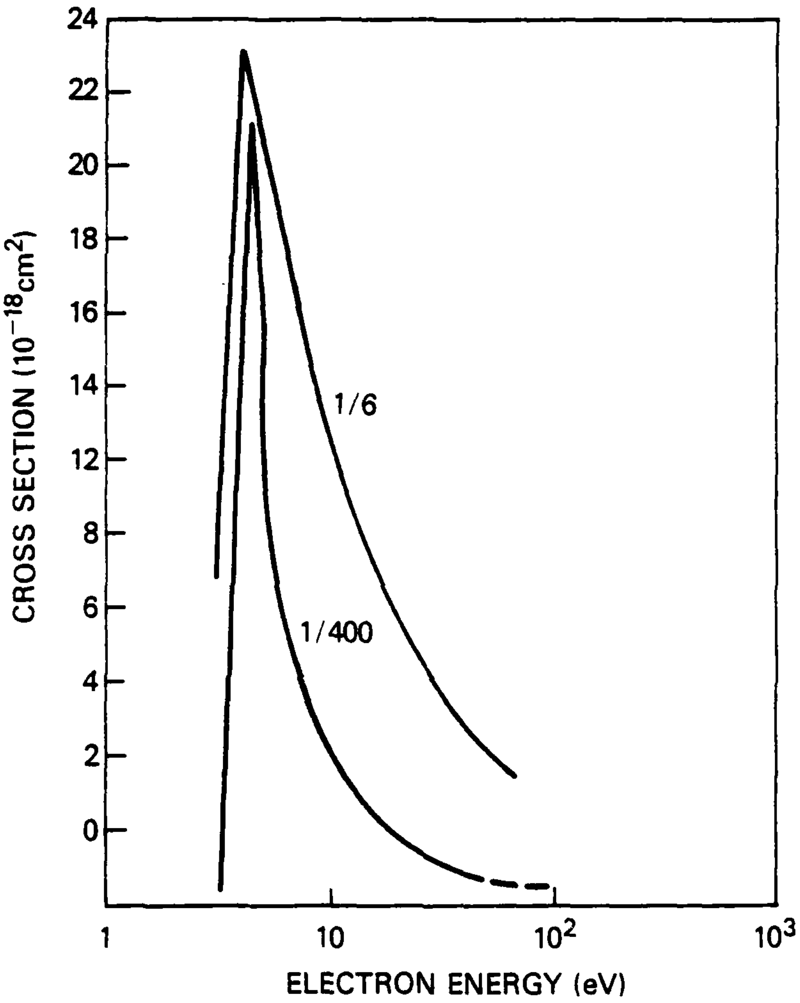

Fig. 2 The emission cross section for the 3914Å excitation from $N_2^+(x)$. The curves 1/6 and 1/400 are from References 16 and 15, and are reduced by factors of 6 and 400, respectively.

The $C^3\pi$ (v = o) state, the upper level for the 3371Å is quenched in collisions with N_2 according to (3)

$$N_2\ [C^3\pi\ (v = o)] + N_2 \rightarrow N_2 + N_2 \tag{3}$$

Where a recommended[11] value for the rate coefficient is $1.12\times10^{-11}cm^3/sec$, based on various measurements (see Ref. 11 for details).

The $C^3\pi$ (o) state is excited by electron impact from the ground state of N_2. This excitation is a transition from a singlet, $^1\Sigma$, to a triplet, $^3\pi$, state and clearly can not be excited by photoabsorption, because it is a forbidden transition. The cross section for the excitation of the $C^3\pi$ state has been measured and calculated by numerous investigators and is reviewed in Ref. 19. Figure 3 shows the 3371Å emission cross section[20] for excitation from the ground state of N_2. In addition to the quenching of the C-state by N_2, it can be deexcited by electron collisions. However, the deexcitation to the $B^3\pi$ state is more effective. On the other hand, the cross section for this process is not known but can be estimated[21]. Other possible sources[22] of the 3371Å excitation is the dissociative recombination of N_4^+ with electrons, where a very small fraction results in the 3371Å emission. However, one must consider the time scale for the formation of N_4^+ in order to estimate its contribution to the 3371Å emission. The coefficient[23] for its formation is $5\times10^{-29}cm^6/sec$, which implies ~ 10μ sec for the N_4^+ formation at a pressure of 5 Torr and hence is negiligible for times of interest.

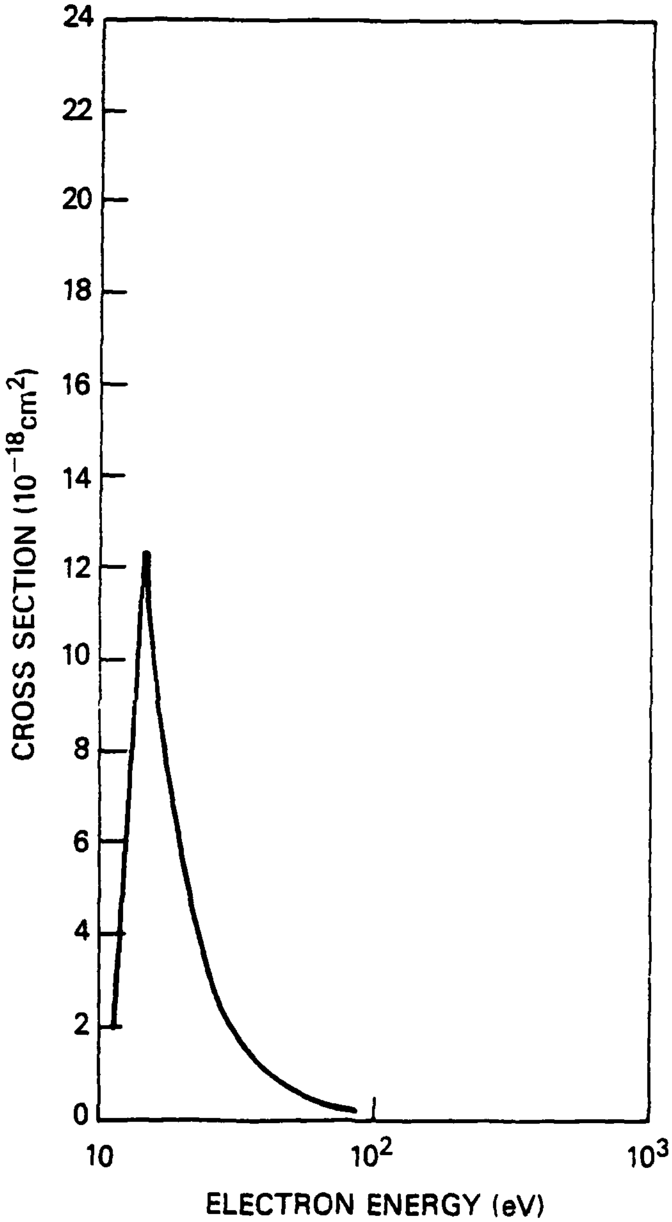

Fig. 3 The emission cross section for the 3371Å due to electron impact on N_2 (Ref. 20).

3. BAND INTENSITY RELATIONS

The line or band intensity for a transition from an upper state, n, to a lower state, n', can be expressed, for an optically thin case, as

$$I = A_{nn'} \, h\nu_{nn'} \, N_n L \tag{4}$$

Here, $A_{nn'}$ is the transition rate, $h\nu_{nn'}$ is the transition energy ($E_{nn'} = h\nu_{nn'}$), N_n is the population density of the excited state, n, and L is the length of the emitting plasma. The quantity that is needed in (4) is N_n which has to be calculated. In the case of an optically thick case, one has to perform the radiative transfer in addition to the calculation of the population density of the upper and the lower states of the transition.

The calculation of N_n can be obtained from the solution of a rate equation which considers all possible production and loss terms that affect the excited state. Obviously, this has to be done in conjunction with a set of rate equations which considers production and decay of the electron density and all relevant species in the plasma. The generation of ionization clearly requires the knowledge of the ionizing source. In the case of the NRL experiment one has to know the flux and the frequency distribution of the ionizing radiation. Once these are measured the above detailed prescription can be followed to determine N_n and hence the plasma parameters.

However, in the absence of a quantitative knowledge of the ionizing radiation, one can calculate the densities of the upper levels assuming a steady state. For example, the population densities of the N_2^+ (B, v = o) and N_2(C,v = o) states can be expressed as

$$N_2^+ (B,0) = \frac{N_e \, N_2^+ \, \langle\sigma v\rangle^+}{A_0^B + q^+ \, N_2 + N_e \, Y^+} \tag{5}$$

$$N_2\ (C,o) = \frac{N_e\ N_2\ \langle\sigma v\rangle^0}{A_0^C + q^0\ N_2 + N_e\ Y^0} \tag{6}$$

Where N_e is the electron density, A_0 is the transition rate for the decay of v=o state, $\langle\sigma v\rangle$ is the excitation rate coefficient, q is the quenching rate coefficient and Y is the deexcitation rate coefficient due to superelastic collisions. The superscripts o and + indicate the process affecting the 3371Å and 3914Å bands which are from a neutral species, N_2, and the ion species, N_2^+, respectively.

Using relations (5) and (6) into equation (4) one obtains

$$I(3914) = A_{00}^B\ E(3914)\ \frac{N_e\ N_2^+\ \langle\sigma v\rangle^+}{A_0^B + q^+\ N_2 + N_e\ Y^+}\ L \tag{7}$$

and

$$I(3371) = A_{00}^C\ E(3371)\ \frac{N_e\ N_2\ \langle\sigma v\rangle^0}{A_{00}^C + q^0\ N_2 + N_e\ Y^0}\ L \tag{8}$$

for the band intensities of the 3914Å and 3371Å, respectively. Here, E(X) is the energy of the band X. And A_{00}^Z is the (o,o) transition rate for band Z. Therefore, the measurements of an absolute intensity of one band and the ratio of the relative intensities of the two bands would provide the necessary information to obtain both the electron density and the electron temperature.

In the absolute intensity relations (see Eq. 7 and 8) and in the ratio of the two, one needs the rate coefficients $\langle\sigma v\rangle^{+}$, $\langle\sigma v\rangle^{0}$ and their ratio $\frac{\langle\sigma v\rangle^{+}}{\langle\sigma v\rangle^{0}}$ as a function of the electron temperature. These rate coefficients and their ratio are shown on Figures 4 and 5. T.ey are obtained from the emission cross sections averaged with the electron velocity over an electron Maxwellian velocity distribution and then multiplied by the appropraite factors to give the rate for the excitation of the (v=o) state.

4. CALCULATIONS OF N_e AND T_e

In the NRL experiment[24] two background gas pressures of 1.5 Torr and 5.0 Torr were utilized. The measured absolute intensities of 3914Å and 3371Å for the case of 1.5 Torr of N_2 were 2.11×10^{8} ergs $cm^{-2}sr^{-1}$ and 4.13×10^{8} ergs cm^{-1} sr^{-1}, respectively. The corresponding intensities at 5 Torr were 1.89×10^{8} erg $cm^{-2}sr^{-1}$ and 3.38×10^{8} erg $cm^{-2}sr^{-1}$, respectively.

The intensities were measured at a distance of 1 cm from the target and at an early time before the plasma has expanded into this region. The length of the emitting plasma is required in the absolute intensity relations (see Eqs. 7 and 8). This length can be determined by placing an aperture[17] in the photoionized region which blocks the ionizing radiation from the background gas except for the aperture region which determines the plasma dimensions. In the absence of an aperture, the measured intensity along the line of sight is composed of emissions from regions of the background gas which have seen different values of the ionizing flux. This is because the intensity of the ionizing radiation varies as $\frac{1}{4\pi R^{2}} e^{-\alpha R}$ where R is the distance from a point source and α is the absorption coefficient. An estimate of the length of the emitting plasma can be made by calculating the relative intensity of the ionizing radiation at different points on the line of sight which is one cm away from the point source and is perpendicular to the laser axis. For the

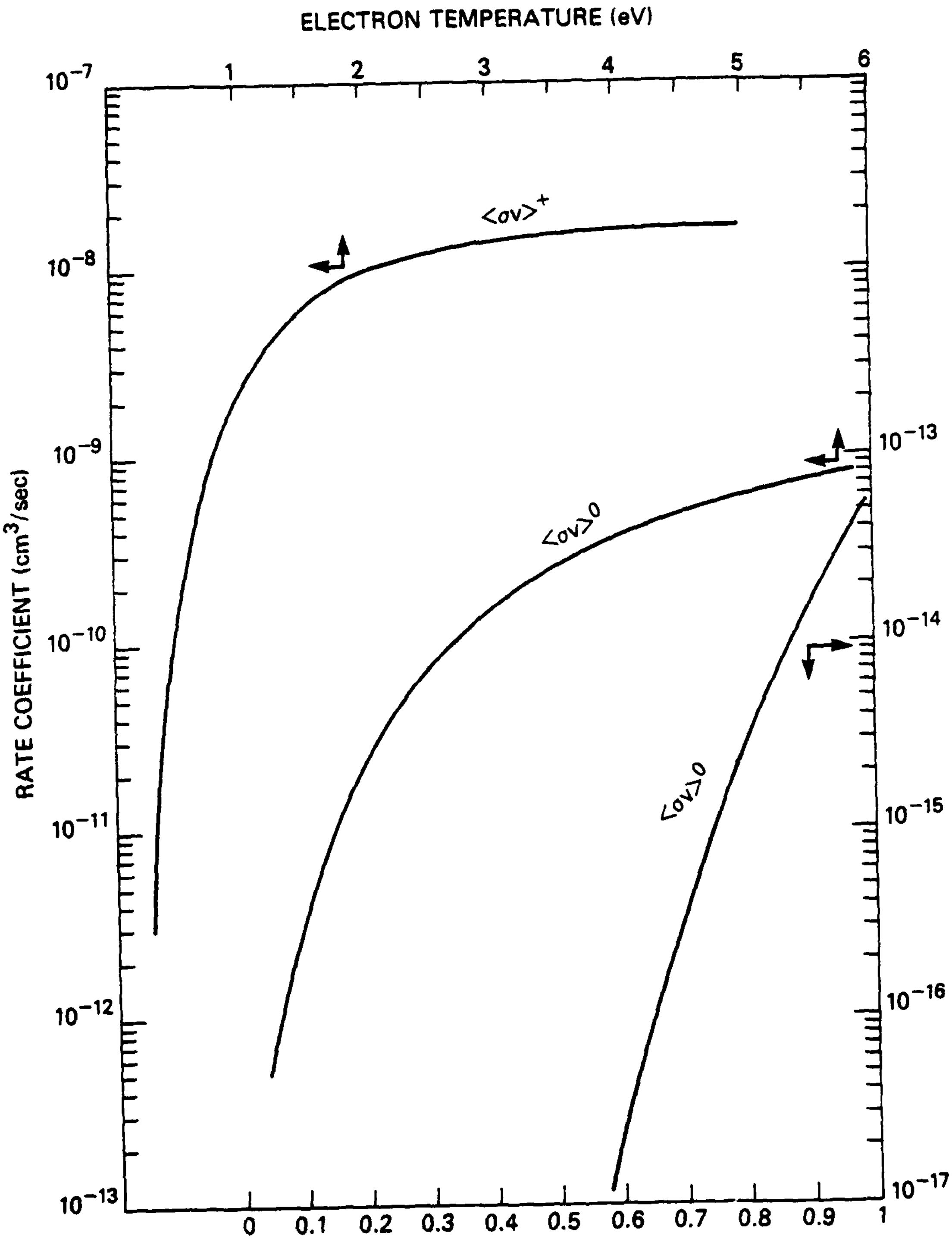

Fig. 4 The electron impact excitation rate coefficients as a function of the electron temperature for $N_2^+(B,0)$ and $N_2(C,0)$ indicated by $<\sigma v>^+$ and $<\sigma v>^0$, respectively.

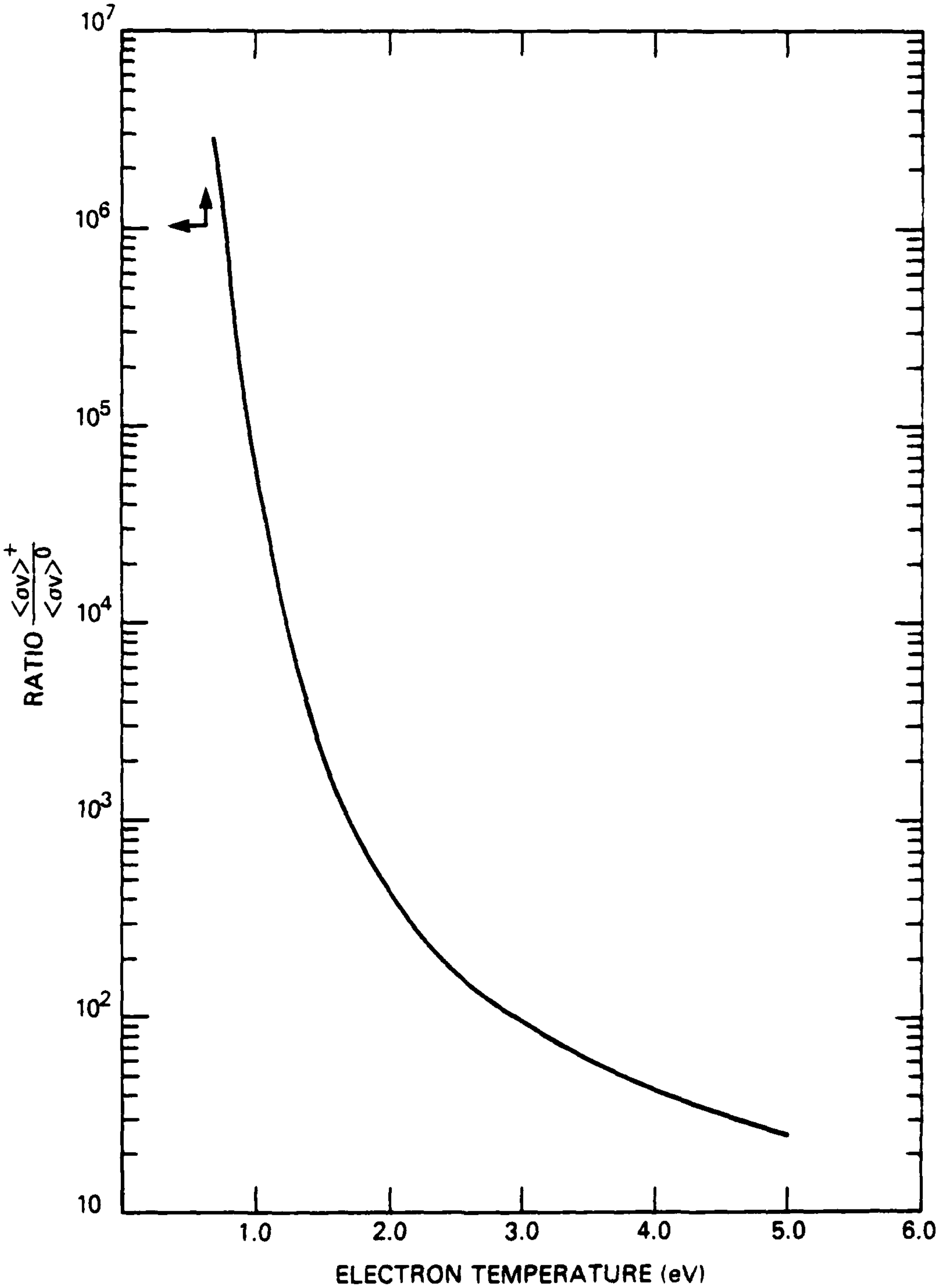

Fig. 5 The ratio of $\langle\sigma v\rangle^+$ to $\langle\sigma v\rangle^0$ as a function of the electron temperature.

case of the 1.5 Torr ~ 75% of the intensities are emitted from 1.5 cm length while at 5 Torr case 85% of the intensities are from a 1.5 cm length. Using these, the measured intensities and intensity relations (7) and (8) in conjunction with Figures 4 and 5 we obtain the following results. For 1.5 Torr T_e = 2.5 eV and N_e = 2.5 x 10^{14} cm^{-3}, on the other hand for the case of 5 Torr we obtain T_e = 1.85 eV and N_e = 5.6 x $10^{14} cm^{-3}$.

5. CONCLUSIONS

The electron density and temperature in the photoionized region of the NRL early time studies can be estimated in the manner described in this report. However, the region where the measurements were made (1 cm from the target) were photoionized by the radiation from the expanding plasma. In order to study the photoionized region (the uv fireball), due to radiation from the debris-nitrogen coupled shell, one must conduct measurements at distances larger then one cm as the spectroscopic measurements[24] indicate. For the 5 Torr case this region is > 1.5 cm.

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